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Heat Recuperator Engineering for an ARL Liquid-Fueled Thermophotovoltaic Power Source Demonstrator

by William R Allmon, Dr C Mike Waits, and Dr Erik D Tolmachoff

ARL-TR-7113 September 2014

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Heat Recuperator Engineering for an ARL Liquid-Fueled Thermophotovoltaic Power Source Demonstrator

William R Allmon, Dr C Mike Waits, and Dr Erik D Tolmachoff
Sensors and Electron Devices Directorate, ARL

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
September 2014	Final	

4. TITLE AND SUBTITLE	
Heat Recuperator Engineering for an ARL Liquid-Fueled Thermophotovoltaic Power Source Demonstrator	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
William R Allmon, Dr C Mike Waits, and Dr Erik D Tolmachoff	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
US Army Research Laboratory ATTN RDRL-SED-E 2800 Powder Mill Road Adelphi, MD 20783-1138	ARL-TR-7113
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Direct thermal-to-electrical conversion shows promise for small-scale portable power sources using logistics and multiple other fuels. Some potential technologies include thermoelectric, thermophotovoltaic (TPV), and thermionic. For these technologies, thermal efficiency is critical to achieve high energy density and thermal-to-electric conversion efficiency. Combustion can be used to convert fuel to heat a surface, but more than 50% of the thermal power of the combustor can be lost to the exhaust. As a result, heat recuperation is absolutely necessary to reclaim this lost energy. This is accomplished by heating the inlet air and fuel going into the microcombustor using the hot exhaust gases from the microcombustor. The US Army Research Laboratory (ARL) is pursuing a concept demonstration to integrate key components of a combustion-based TPV power source including a microcombustor and heat recuperator. The heat recuperator employs counter flow and microchannel heat transfer to enable high transfer rates in compact form due to a high surface area-to-volume ratio, but challenges exist with pressure drop tradeoffs and fabrication complexity. This report focuses on identifying appropriate materials and fabrication limitations for a microchannel heat recuperator preliminary design.

15. SUBJECT TERMS

Heat recuperator, micro channels, thermophotovoltaic, power source, microcombustor, microreactor, portable power

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Unclassified	Unclassified	Unclassified	UU	28	301-394-0117

Standard Form 298 (Rev. 8/98)
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Contents

List of Figures

1. Background

Direct thermal-to-electrical conversion shows promise for small-scale portable power sources using logistics and multiple other fuels. Some potential technologies include thermoelectric, thermophotovoltaic (TPV), and thermionic. For these technologies, thermal efficiency is critical to achieve high energy density and thermal-to-electric conversion efficiency. Combustion can be used to convert fuel to heat a surface. High efficiency requires temperatures above 500 °C for thermoelectric and TPV. The exhaust gas will be above this temperature, but more than 50% of the thermal power of the combustor can be lost to the exhaust as it has a very low resistive path. As a result, heat recirculation or heat recuperation is absolutely necessary to reclaim this lost energy. This is accomplished by heating the inlet air and fuel going into the microcombustor using the hot exhaust gases from the microcombustor. The US Army Research Laboratory (ARL) is pursuing a concept demonstration to integrate key components of a combustion-based TPV power source including a microcombustor and heat recuperator.[1]

Figure 1 describes the primary components of a TPV system: a heat source, an emitter, and a photovoltaic converter. The heat source supplies thermal energy to the emitter, which radiates the energy across a gap to the photovoltaic cell or an array of photovoltaic cells. The photovoltaic cell(s) then converts the thermal radiation to electrical energy, which can be delivered to a load or conditioning circuitry. Optical filters between the emitter and the photovoltaic cell (not included in Fig. 1), as well as the reflectors deposited on the backside of the photovoltaic cell, are also common components. The optical cavity between the emitter and photovoltaic cell is often held under vacuum to minimize conduction and convective heat transfer.[1]

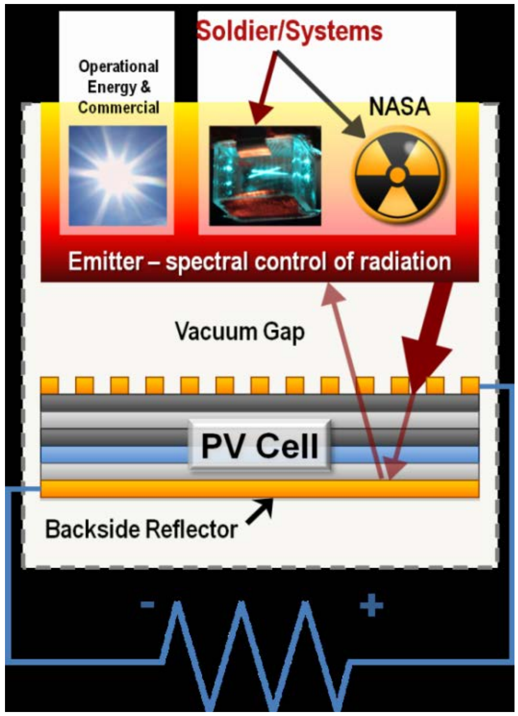

Fig. 1 Primary components of thermophotovoltaic energy converter[1]

For this concept demonstrator, the exterior of the heat recuperator and microcombustor will also be held at vacuum to minimize heat loss. The heat recuperator employs counter flow, where the microcombustor exhaust enters the recuperator at one end and the inlet air and fuel enters at the other end at ambient temperature. The heat recuperator employs microchannel heat transfer to enable high transfer rates in compact form due to a high surface area-to-volume ratio, but challenges exist with pressure drop tradeoffs and fabrication complexity. The heat recuperator design is focused on several factors to include the ability to integrate with the thin wide profile of the microcombustor, identify appropriate materials and fabrication limitations, validate analytical models used to determine performance, and explore liquid vaporization of fuel. This report focuses on identifying appropriate materials and fabrication limitations for a microchannel heat recuperator preliminary design.

2. Material Selection

To handle the high temperature demands and retain a protective oxide coating under conditions of cyclic exposure to high temperature, a high nickel specialty alloy known as Inconel 600™ was selected for the heat recuperator. It is often used in furnace and heat treating fields, which require resistance to oxidation and to furnace atmospheres. We are currently using a similar Inconel grade known as HX for the microcombustor. Using the similar material for the microcombustor, heat recuperator, and the inlet and outlet tubing ensures thermal expansion compatibility. Unlike conventional metals such as carbon steel and 304 or 316 stainless steel, Inconel maintains a reasonable amount of strength and resists oxidation at these high temperatures. The strength of the material is of particular importance since the walls of the microcombustor and heat recuperator are very thin and create part of the vacuum wall. Other Inconel alloys are available, but Inconel 600 is well characterized, readily available in tube, sheet, and bar in the required sizes, and available in small quantities for our low volume purposes. Inconel 600 is slightly more machinable than 304 stainless steel and slightly less machinable than 303 stainless. While the high temperatures seem well suited for ceramics, these materials are more brittle and fragile.

3. Thermal and Fluidic Design Analysis

The preliminary design was chosen as a tradeoff between performance and pressure drop. The channels were modeled using a ε-NTU method with a previously published Nusselt number.[2] The channel dimensions offered a tradeoff between pressure drop and fin efficiency, and the channel length was set to 1.97 inches and the thickness of the wall was set for machinability. Due to thermal conduction and the short channel lengths for small-scale/portable power, the channel wall thickness plays an important part. Thus, a reasonable minimum thickness of 0.020 inches was chosen. The details of the preliminary design are not the focus of this report and will be published in a future report. With the anticipated flow rate, COMSOL simulation suggests the effectiveness in the range of 0.6 to 0.7 can be achieved with this design.[3] Conducting a first-order optimization analysis of the geometry, a heat recuperator with 3 rectangular channel openings of 0.197 inches high and 0.039 inches wide for each direction of flow was found to provide good performance (Fig. 2).

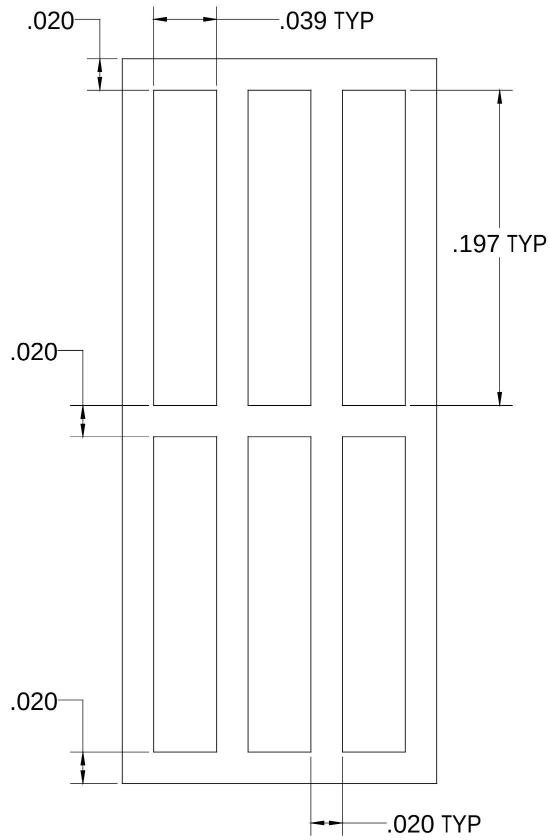

Fig. 2 A heat recuperator with 3 rectangular channel openings for each direction of flow

4. Fabrication Method

To create the heat recuperator with this design geometry, an assembly of the following custom fabricated parts—base, cover, ends, and tubes—are required (Fig. 3). The most difficult part to fabricate is the base. It is fabricated using wire electric discharge machining (EDM) to create narrow deep cuts and thin features not possible using standard milling. Wire EDM does not put stress on the part, since it is a slow erosion process. In contrast, milling puts stress on the part as the tool moves and cuts away material. In addition, mill tooling small enough to cut these narrow channels is not long enough to reach to the bottom of these deep channels.

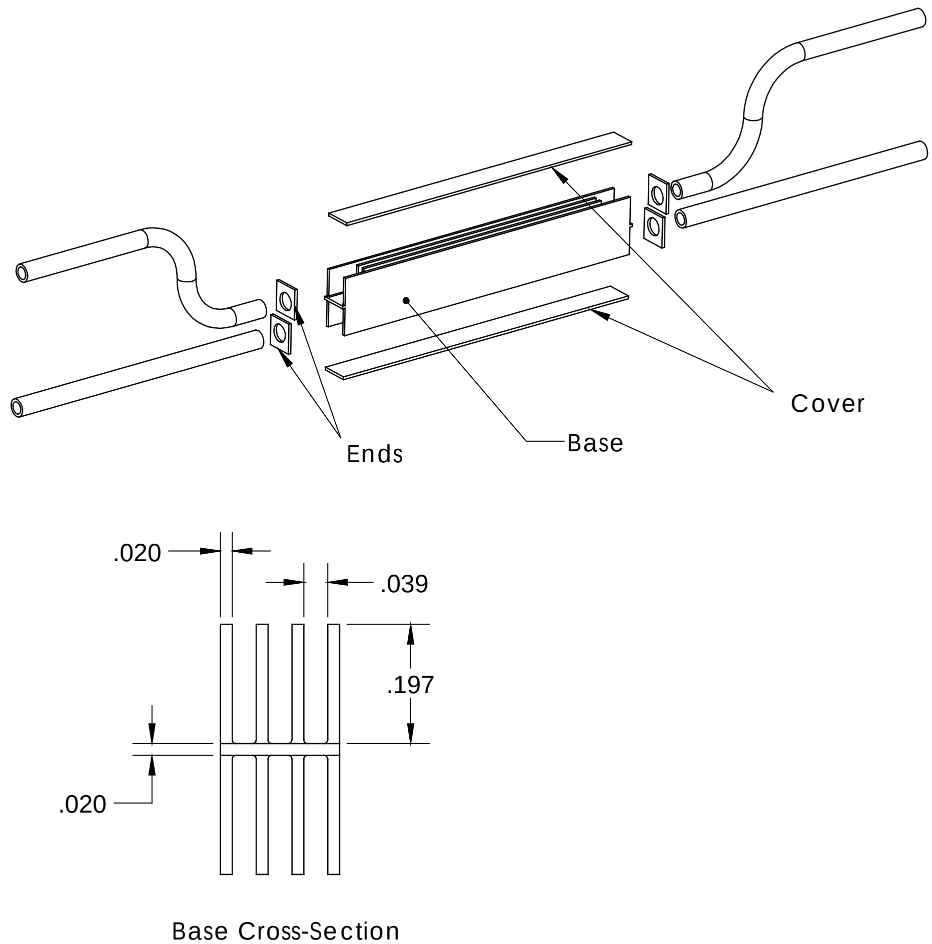

Fig. 3 The heat recuperator showing the assembly of the custom fabricated parts

Other methods of fabrication, such as direct metal laser sintering (DMLS), were considered. DMLS does not provide the tolerance control required, making post-machining necessary prior to welding. In addition, parts designed for DMLS require material to be added in certain places to support the part during fabrication. This added material is removed through post-machining. With this much post-machining, it seems more economical to fabricate the parts directly with wire EDM.

The parts are joined together to form the heat recuperator assembly. The thin features of the parts require precise welding to join them together. To accomplish this, electron beam welding (EBW) was selected. EBW is a fusion weld process where a beam of high velocity electrons is applied to the junction of two parts melting them together. The two parts must have gaps of less than 10% of thickness of the thinnest part (0.002 inch for this design). EBW is very controlled, can be used on very small assemblies, and can provide high levels of weld penetration. Since the base is fabricated using wire EDM, the EDM recast layer of carbonized material must be removed prior to welding. The welding contractor removes this recast layer mechanically or chemically.

Typically, removal of 0.0005 inch is adequate. The removal cannot be done with abrasive media such as sand or beads since the abrasive media tends to get embedded in the base material leading to weld joint contamination.

Since the heat recuperator is part of the vacuum wall, it is critical the welds provide adequate sealing and structural integrity. The EBW contractor will leak test the assembly by pressurizing the interior with helium to 14.7 psig and sniffing the exterior with a helium leak detector with the leak threshold set at 1 x 10-9 std cc/s. This allows leaks to be located and welds to be reworked as necessary.

5. Weld Penetration Analysis

As part of the design, a stress analysis was performed to determine the weld penetration required to maintain structural integrity of the heat recuperator assembly under vacuum. The analysis was performed using Solid Works Simulation. The assembly worse case was modeled in simplified form as a shelled out chamber with a wall the thickness equal to the weld penetration. The case analyzed had a wall thickness of 0.0025 inches and outside dimensions of 0.200 x 0.225 inches —a worst-case equivalent model of the upper or lower 3 channels. Since the cover is only welded to the outer fins and the interior is pressurized, the center fins provide no support. Figure 4 shows the model used in the analysis that is the entire width of the recuperator and the height of one 3-channel side. A pressure of 14.7 psi was applied to all the inside surfaces and one small end was fixed to allow the solver to function. The following material properties provided by Special Metals Publication SMC-027 for Inconel 600 operating at 1600 °F (871 °C) were used:

Name:	**Inconel 600 at 1600 °F**
Model type:	**Linear Elastic Isotropic**
Default failure criterion:	**Max von Mises Stress**
Yield strength:	**17000 psi**
Tensile strength:	**22000 psi**
Elastic modulus:	**2.28e+007 psi**
Poisson's ratio:	**0.329**
Mass density:	**0.306 lb/in^3**
Shear modulus:	**8.58e+006 psi**
Thermal expansion coefficient:	**9.1e-006 /Fahrenheit**

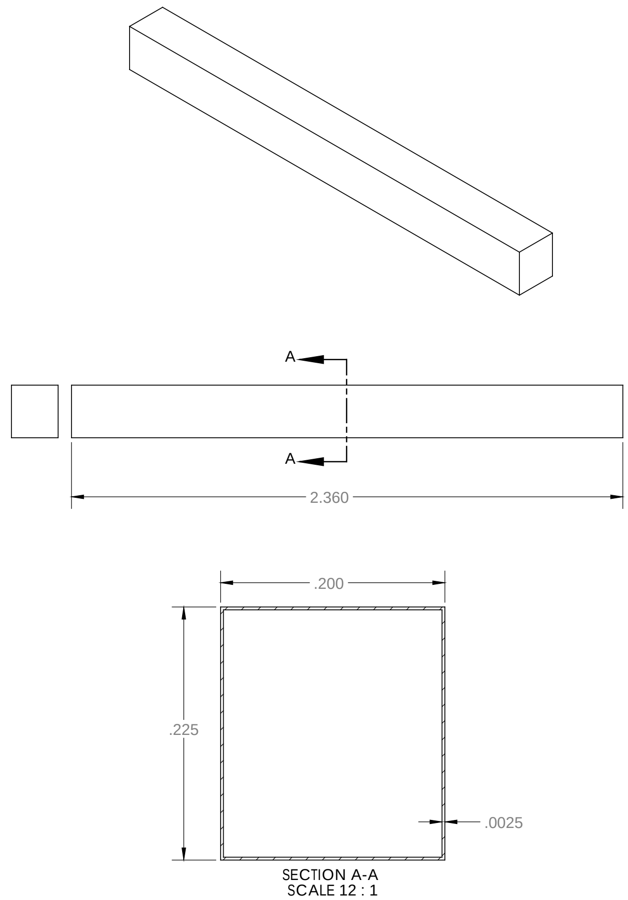

Fig. 4   Solid Works Simulation model

Figure 5 shows the refined mesh of the walls following several meshes and solving iterations.

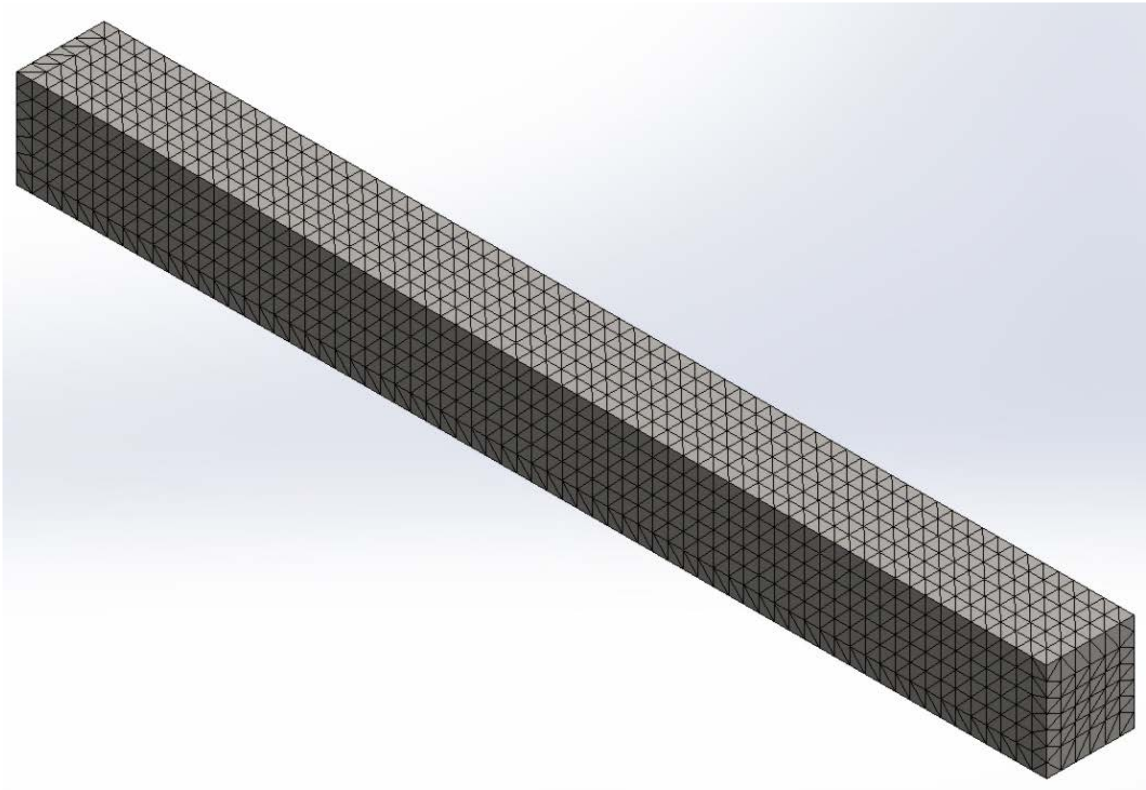

Fig. 5 The refined mesh

From Fig. 6, the maximum von Mises stress is in the corners and in the middle of the surface. It is shown as bright green. Using the scale on the right, bright green is near the yield strength of the Inconel 600 at 1600 °F (871 °C). It is believed this case is worse than will be seen in service since the temperature is likely not to be 1600 °F for the whole assembly. In addition, the wall thickness is 0.020 inches. Only at the weld will it be 0.0025 inches. As a result, less deflection and thus less stress is likely throughout the assembly. To add a factor of safety, the weld penetration call out in the weldment drawing is a minimum of 0.005 inches.

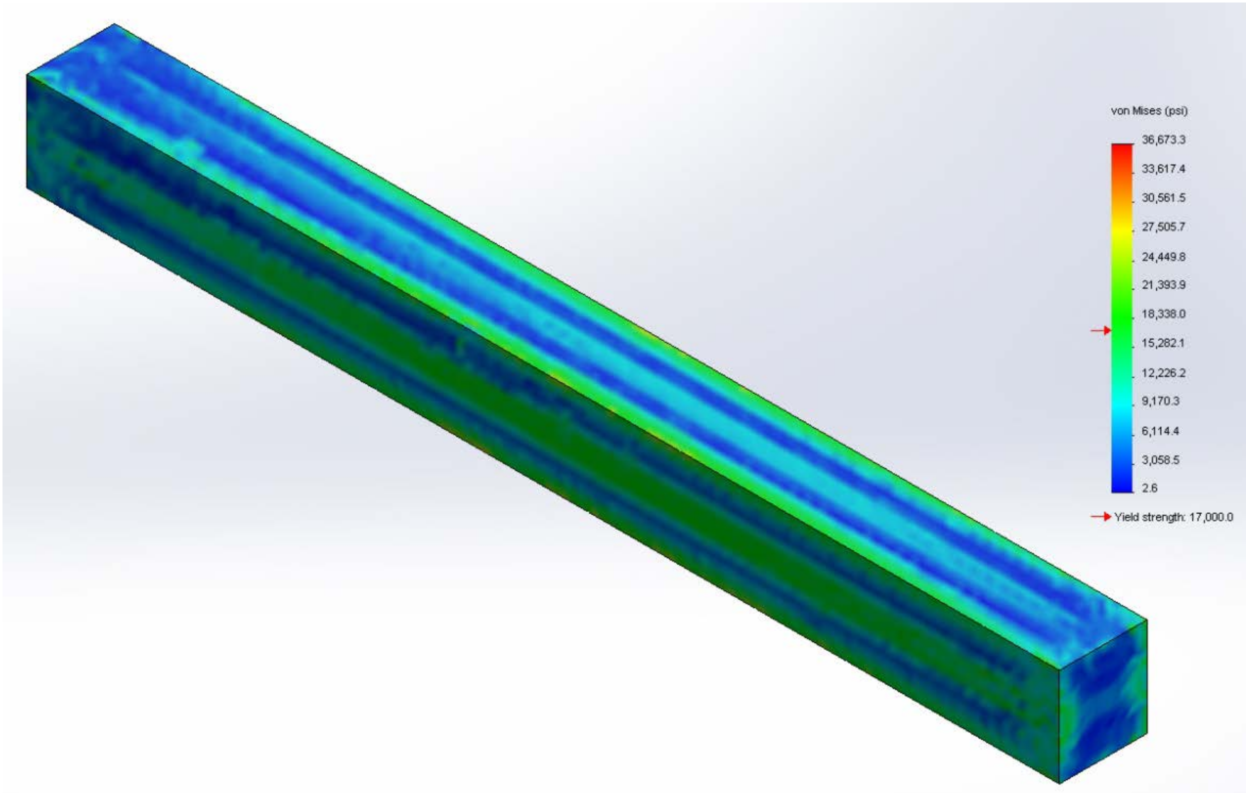

Fig. 6 Von Mises stress

Figure 7 shows the deflection of the model. The deflection shown in red is a maxium at the center of the surface and is 0.002 inches.

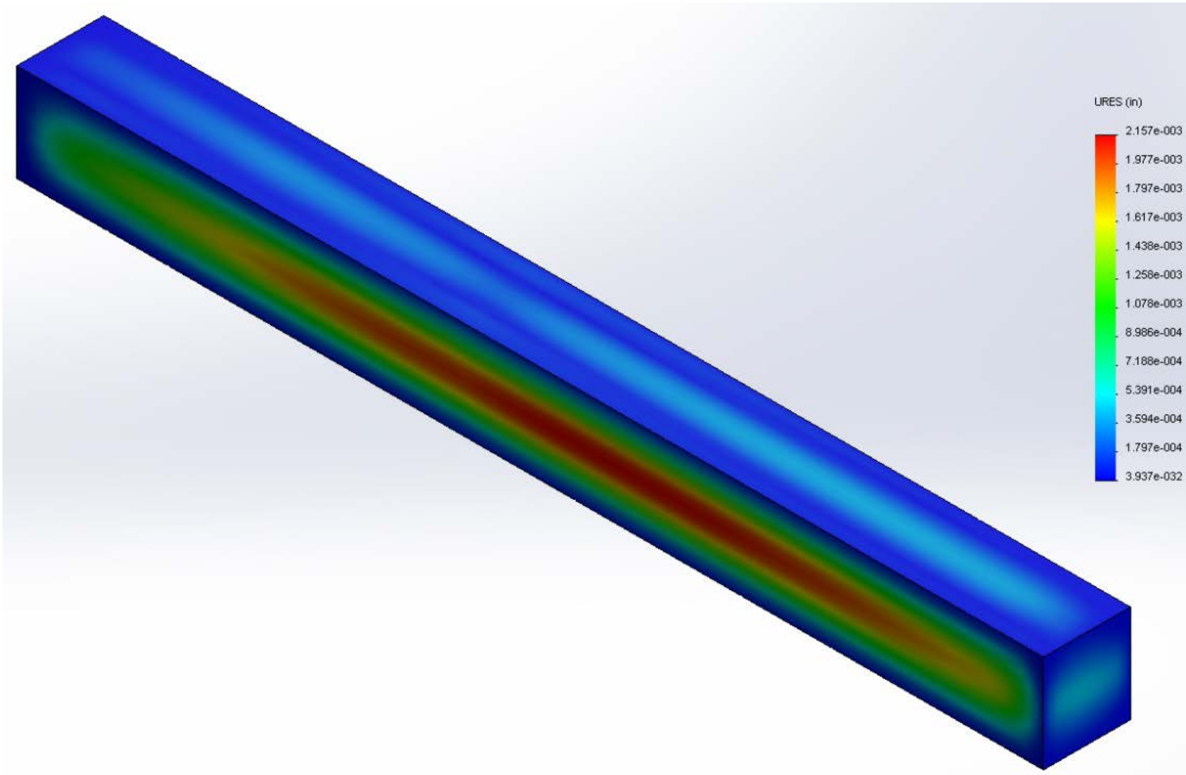

Fig. 7 Deflection

Complete detailed fabrication drawings showing the parts and assembly with dimensions and notes can be found in the appendix.

6. Conclusion

ARL created a preliminary design of a high temperature heat recuperator for use with a microcombustor as part of a TPV power source. The heat recuperator is critical to the efficiency of such a system through reuse of the heat that would otherwise be lost to ambient. The recuperator is made of a high nickel specialty alloy known as Inconel 600 and fabricated using wire EDM and EBW. An analysis of the required weld penetration was conducted to ensure sealing and structural integrity of the heat recuperator since the exterior is in vacuum and the interior is at or near ambient pressure.

7. References

1. Waits MC. Thermophotovoltaic energy conversion for personal power sources. Adelphi (MD): US Army Research Laboratory (US); February 2012. Report No.: ARL-TR-5942.

2. Smith AN, Nochetto H. Laminar thermally developing flow in rectangular channels and parallel plates: uniform heat flux. Heat Mass Transfer. DOI 10.1007/s00231-014-1363-8, 2014.

3. Smith AN, Nochetto H, Waits CM. Influence of axial conduction in the design of a compact recuperator for catalytic combustor based portable power generation. Proceedings Comsol Conference 2014.

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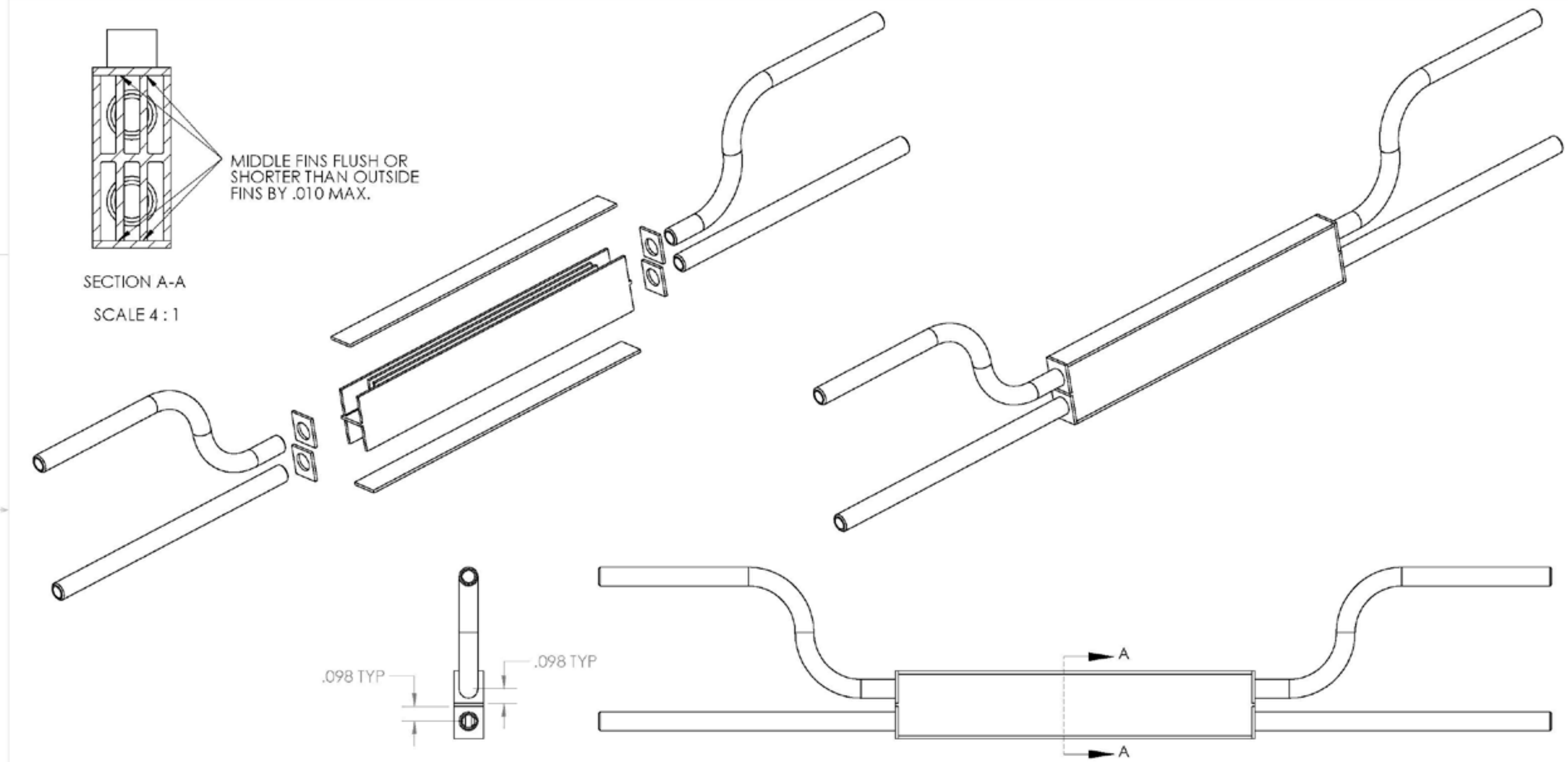
Appendix. Part and Assembly Fabrication Drawings

This appendix includes detailed part and assembly fabrication drawings with dimensions, tolerances, material, finish, and other notes.

The order of drawings is as follows:

- Heat Exchanger ASSY-V2
- Heat Exchanger WELDMENT-V2
- Heat Exchanger Base-V2-R1
- Heat Exchanger Cover-V2-R1
- Inlet-Outlet Ends-3-V2-R2
- Tube-2-Bends-V2-R1
- Tube-Straight-V2-R1



NOTES:
1. INTERPRET DIMENSIONS IAW ASME Y14.5-2009.
2. REMOVE ALL BURRS AND BREAK SHARP EDGES.
3. MATERIAL: SEE INDIVIDUAL PART DRAWINGS.
4. FINISH: SEE INDIVIDUAL PART DRAWINGS. CLEAN AND DEGREASE PARTS IN PREPARATION FOR ELECTRON BEAM WELDING.
5. GAPS BETWEEN PARTS IN AREAS OF WELD SHALL BE NO MORE THAN .002 INCH. SEE WELDMENT DRAWING.
6. PACKAGE PARTS TO PROTECT IN SHIPPING AND MAINTAIN CLEANLINESS.

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TITLE:
HEAT EXCHANGER ASSY-V2

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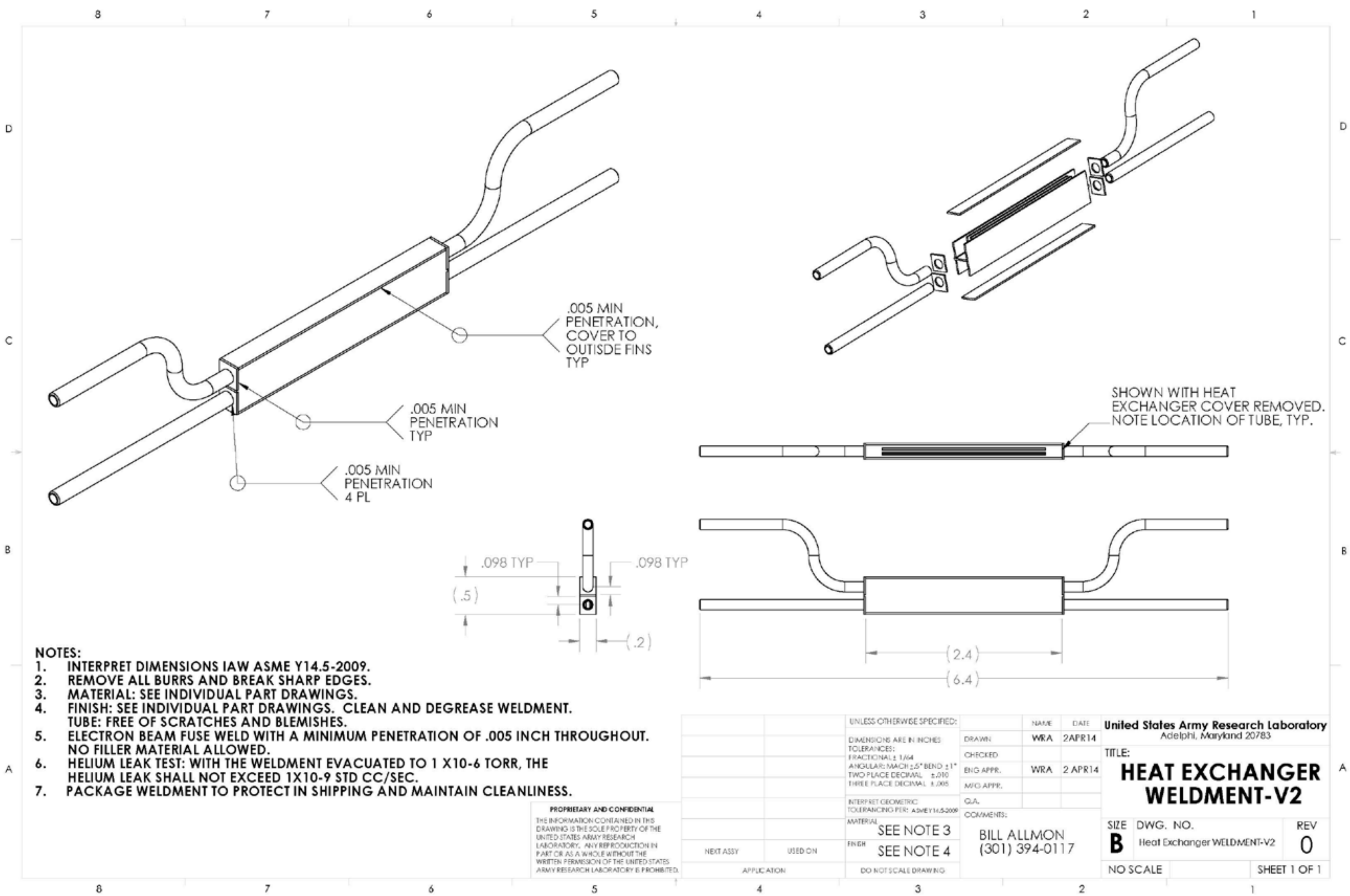
.005 MIN PENETRATION, COVER TO OUTISDE FINS TYP
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SHOWN WITH HEAT EXCHANGER COVER REMOVED. NOTE LOCATION OF TUBE, TYP.
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.098 TYP
(.5)
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3. MATERIAL: SEE INDIVIDUAL PART DRAWINGS.
4. FINISH: SEE INDIVIDUAL PART DRAWINGS. CLEAN AND DEGREASE WELDMENT. TUBE: FREE OF SCRATCHES AND BLEMISHES.
5. ELECTRON BEAM FUSE WELD WITH A MINIMUM PENETRATION OF .005 INCH THROUGHOUT. NO FILLER MATERIAL ALLOWED.
6. HELIUM LEAK TEST: WITH THE WELDMENT EVACUATED TO 1 X10-6 TORR, THE HELIUM LEAK SHALL NOT EXCEED 1X10-9 STD CC/SEC.
7. PACKAGE WELDMENT TO PROTECT IN SHIPPING AND MAINTAIN CLEANLINESS.
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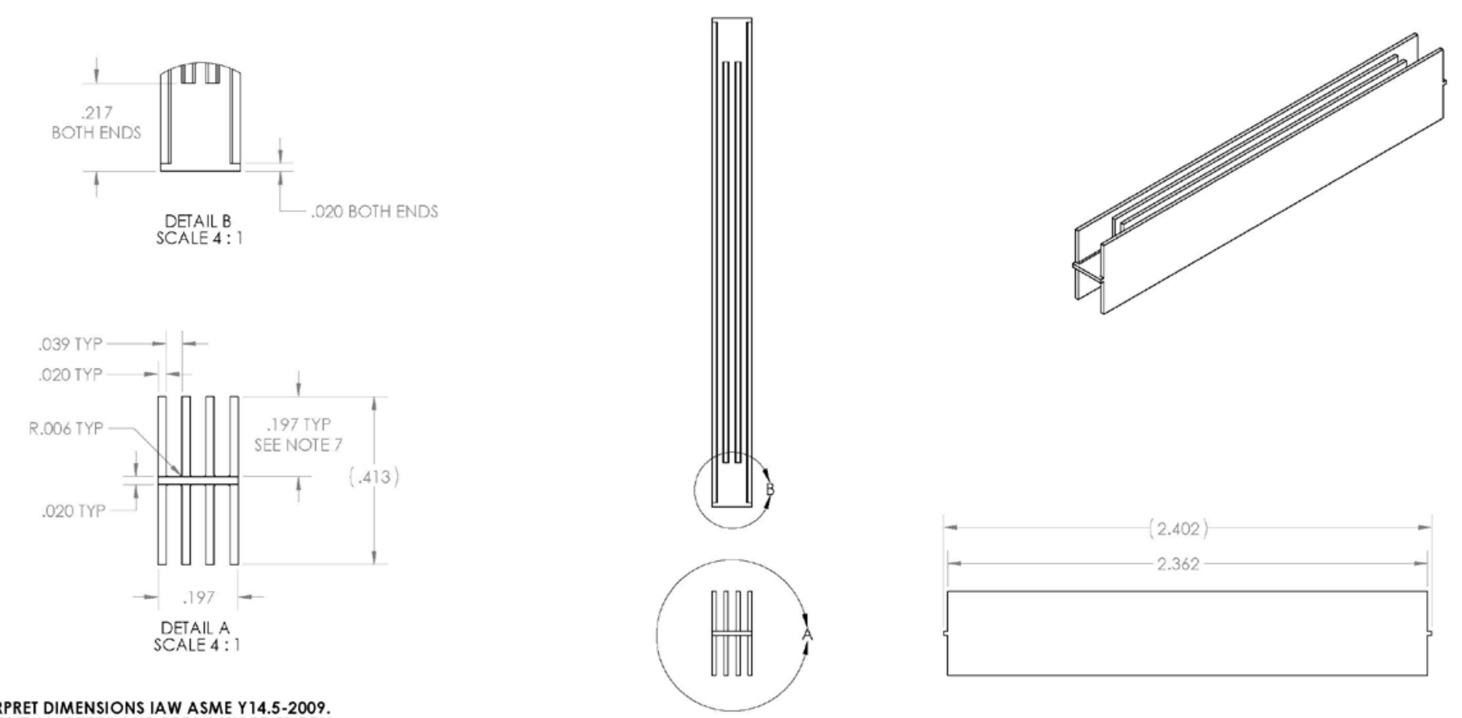

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5. GAPS BETWEEN PARTS IN AREAS OF WELD SHALL BE NO MORE THAN .002 INCH. SEE ASSEMBLY AND WELDMENT DRAWINGS.
6. PACKAGE PARTS TO PROTECT IN SHIPPING AND MAINTAIN CLEANLINESS.
7. MIDDLE FINS FLUSH OR SHORTER THAN OUTSIDE FINS BY .010 MAX.

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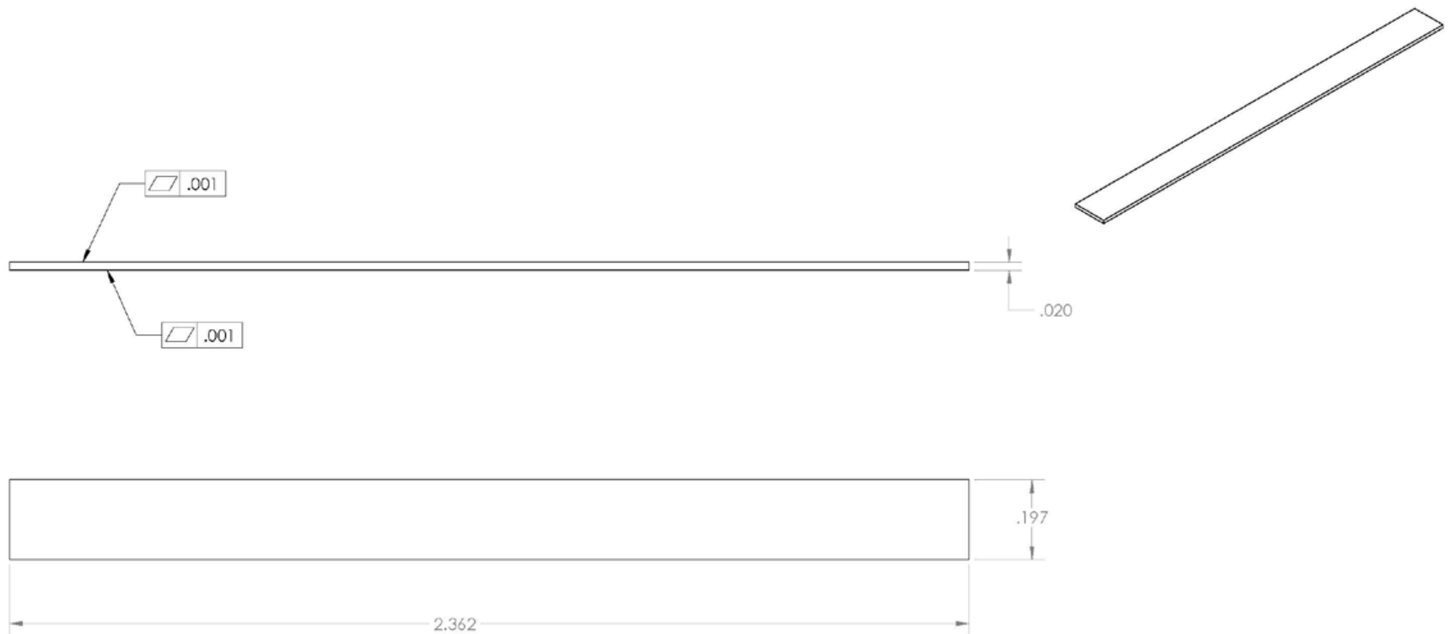

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TITLE:
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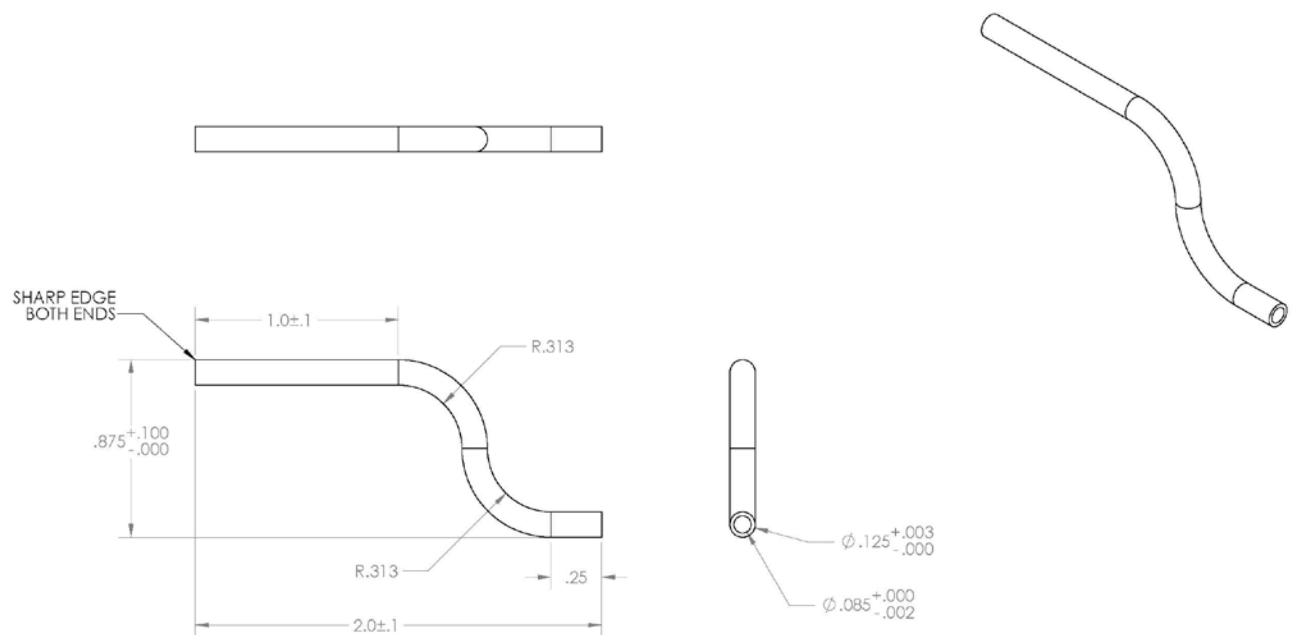

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DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	WRA	30JUN14
CHECKED		
ENG APPR.	WRA	30JUN14
MFG APPR.		
Q.A.		

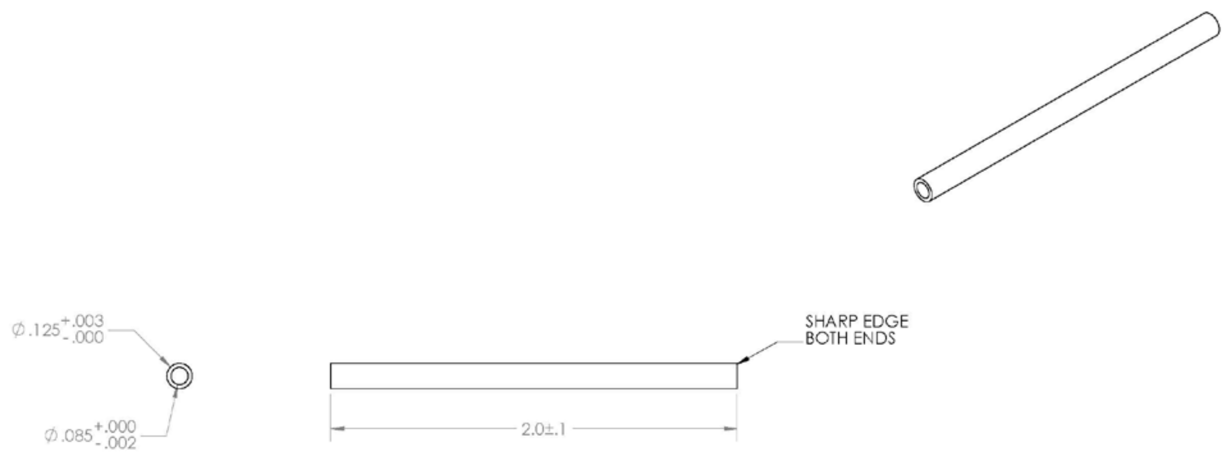
COMMENTS:
BILL ALLMON
(301) 394-0117

United States Army Research Laboratory
Adelphi, Maryland 20783

TITLE:
TUBE, 2 BENDS-V2

SIZE	DWG. NO.	REV
B	Tube-2-Bends-V2-R1	1

NO SCALE | SHEET 1 OF 1



NOTES:

1. INTERPRET DIMENSIONS IAW ASME Y14.5-2009.
2. REMOVE ALL BURRS AND BREAK SHARP EDGES UNLESS OTHERWISE SPECIFIED.
3. MATERIAL: .125 O.D. X .085 I.D. INCONEL 600 PER ASTM B163 , FULLY ANNEALED, SUITABLE FOR BENDING AND FLARING.
4. FINISH: ALL SURFACES SHALL BE 32 OR BETTER UNLESS OTHERWISE NOTED. FREE OF SCRATCHES AND BLEMISHES. PART SHALL BE CLEAN AND SCALE-FREE, CLEAN, AND DEGREASED.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/64
ANGULAR: MACH ±.5° BEND ±1°
TWO PLACE DECIMAL ±.010
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5-2009
MATERIAL SEE NOTE 3
FINISH SEE NOTE 4
DO NOT SCALE DRAWING

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MFG APPR.		
Q.A.		

COMMENTS:
BILL ALLMON
(301) 394-0117

United States Army Research Laboratory
Adelphi, Maryland 20783

TITLE:

TUBE, STRAIGHT-V2

SIZE	DWG. NO.	REV
B	Tube-Straight-V2-R1	1

NO SCALE   SHEET 1 OF 1

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
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